Cosmology with Radio Surveys

Prof. Catherine Cress
Centre for High Performance Computing / Univ. of the Western Cape (South Africa)

Rencontres du Vietnam, 2 August 2013
Outline

Radio Telescopes (incl SKA split site details)
Radio emission mechanisms: continuum sources vs HI sources
Questions in cosmology + Probes in the radio

Results:

1. Forecasting cosmological constraints using future HI surveys
2. Forecasting cosmological constraints using future radio continuum surveys
3. Clustering and bias of radio continuum sources in FIRST survey
4. Clustering and bias of HI sources in ALFALFA
5. Exploring probes of GR using HI data

Reflections
Radio Telescopes

Interferometers:
- JVLA
- GMRT
- WSRT
- eMerlin
- eMerlin
- ASKAP
- MeerKAT
- LOFAR
- PAPER
- MWA
- SKA

Single Dish:
- GBT
- Arecibo
- Effelsberg
- Parkes
Square Kilometer Array (2018 & beyond)
Spilt between South Africa & Australia
4 telescopes: Dish_SA, Dish_A, Low_AA, Dense_AA

Currently in SA: KAT 7
Next: MeerKAT (64 dishes)
Square Kilometer Array (2018 & beyond)
Spilt between South Africa & Australia
4 telescopes: Dish_SA, Dish_A, Low_AA, Dense_AA

Currently in SA: KAT 7 + people
Next: MeerKAT (64 dishes)
The SKA will be constructed in two phases:

**Phase one**

- 190 SKA dishes and 64 MeerKAT dishes equipped with single pixel feeds will be located in South Africa (SKA1 dish mid).

- 60 SKA dishes and 36 ASKAP dishes equipped with phased array feeds will be located in Australia (SKA1 dish survey).

- 50 stations of low frequency aperture array antennas, with about 10 000 antennas per station, will be located in Australia (SKA1 AA low).

**Phase two**

- The dish array will be extended to about 3 000 dishes with a maximum separation of 3 000 km across Southern Africa (SKA2 dish mid).

- The low frequency aperture arrays will be extended to 250 stations in Australia (SKA2 AA low).

- A new component comprising 250 mid frequency aperture array array stations will be located in South Africa (SKA2 AA mid).
Radio emission mechanisms

Line emission/absorption:
- HI (21cm hyperfine transition)
- Molecular lines eg CO
- Masers
- Radio recombination lines

Continuum emission:
- Synchrotron
- Free-free
- Inverse Compton
- Blackbody
Radio galaxy:
* synchrotron emission from jets of charged particles associated with black hole AGN at centre
* see easily at high redshift => **huge volumes** but no z

Starforming galaxy:
* radio continuum from synchrotron and free-free
* fainter than AGN

HI (neutral hydrogen)
Line so redshift and velocities in galaxies
Faint so low-z
Questions in Cosmology
Dark matter/energy: What, How much? Or is GR wrong?
Initial conditions?

Probe by:
* Background expansion measures (eg lum distance, angular diam dist: standard candles and rulers)
* Evolution of density fluctuations
* Exotic effects of GR modification

SKA focus 2004:
BAO (standard ruler) using HI survey
Weak Lensing – shear
1. Cosmology with future HI radio surveys

With SKA, redshift survey to z>1, half sky .. fantastic! But when?

BAO
clustering evolution
redshift space distortions
etc ..
1. Cosmology with future HI surveys: ISW example

Integrated Sachs Wolfe anisotropies

Induces a secondary layer of large-scale anisotropies

Primary anisotropies

No ISW

Matter-dominated Universe

ISW

Varying gravitational potential

Curvature or DE-dominated Universe
1. Cosmology with future HI surveys: ISW example

Dark Energy from dynamical scalar field?

* quintessence: sound speed constant: $c_s = 1$
* other models like k-essence (with non-standard kinetic term): $c_s \neq 1$

Constraints on DE sound speeds possible for low speeds using ISW “tomography”

Torres-Rodriguez & Cress MNRAS 2008
2. Cosmology with Future Radio Continuum Surveys (no redshifts) (as in Raccanelli.. CC… et al)

**Surveys:** EMU on ASKAP + WODAN on WRST (full sky, $3 \times 10^7$ sources)

1. Power spectrum (angular)
2. Lensing magnification
3. ISW (CMB x radio)

Testing gravity:

Changes to background expansion fluctuation growth function of $\eta, \mu$
2. Cosmology with Future Radio Continuum Surveys
(as in Raccanelli.. CC... et al)

Angular power spectrum

Probe non-gaussian initial conditions?
2. Cosmology with Future Radio Continuum Surveys
(as in Raccanelli.. CC… et al)

Lensing Magnification

Cross correlate z>1 radio sources with lower-z tracers of structure (eg EMUxDES, Panstarrs)

Must be able to identify all low-z radio sources

Sensitive to high-z flux distribution
2. Cosmology with Future Radio Continuum Surveys
(as in Raccanelli.. CC... et al)

**ISW:**

CMB temp x number radio gals
2. Cosmology with Future Radio Continuum Surveys
(as in Raccanelli.. CC... et al)

Constraints on modified gravity parameters:

\(w(z)\) constraints:
Cosmology with Radio Continuum Surveys…

What can be done with real data available now?

3. Measuring the bias of radio galaxies in FIRST using matching to SDSS
History of radio continuum clustering measurements

Webster (76), Peacock & Nicholson (91)
Cress (96) – first high significance measurement of angular clustering of radio sources
Magliocchetti (98), Overzier(03), Blake & Wall(02) – repeats/disputes/other radio surveys
Blake et al (04) – agreement: beware sidelobes!

Cress et al (96)
Blake et al (04)

Spatial correlation function inferences, bias indications
What is bias?

Relationship between dark matter and luminous matter

\[ \xi(r, z) = b^2(M_{\text{eff}}, z)\xi_{\text{DM}}(r, z) \]

Gaussian Bias: modulating density background
The role of bias in cosmology projects using radio continuum sources

Bias assumptions in tests of modified gravity, non-gaussianity (Raccanelli et al 2011, Xia et al, etc.)

Bias unknown: compare Raccanelli et al 2008 (use NVSS/WMAP correlation & ISW to check Λ)
The role of bias in cosmology projects using radio continuum sources

Bias assumptions in tests of non-gaussianity (Xia et al, etc.)
3. Probe bias at high-z using FIRST and SDSS combination

- Know average z-distribution of all FIRST sources from small-field obs & $S^3$ model
- Remove SDSS-matched sources from FIRST catalog (with photo-z's)
- Measure Clustering of Unmatched sources
  \[ \frac{dN}{dz_{\text{unmatched}}} = \frac{dN}{dz_{\text{all}}} - \frac{dN}{dz_{\text{matched}}} \]
What do we measure for bias?

At $\theta = 0.4^\circ$, $z_{av} \sim 0.7$:

$b = 3.0 \pm 0.3$

Passmoor et al 2012
Other probes of bias

Bias of optically matched galaxies in 3 slices
Move from clustering of radio continuum sources to ...

clustering of HI galaxies ...

...still with real data
4. Clustering in current HI surveys

as in Passmoor, CC et al (2011)

HIPASS Survey
- Area = 20 000 deg²
- Depth $z \approx 0.02$
- Has 4315 HI sources

ALFALFA Survey
- Area $\approx 400$ deg²
- Depth $z \approx 0.06$
- Has 1796 HI sources

HI-selected galaxies antibiased wrt to DM!
Less massive galaxies more antibiased?
NB for cosmological predictions for SKA (and galaxy evolution)
5. Using galaxies detected in HI to test gravity?

Johnston .. CC et al.

To test gravity: compare gravitational potential causing peculiar velocities of galaxies with gravitational potential seen by light (through eg lensing observations)

Potentials from peculiar velocity info using eg Tully-Fisher relation

Bayesian priors:
Use galaxy density and and expected power spectrum

Could reconstruct potentials $z<0.3$
Summary

Radio Telescopes (incl SKA splitsite details)
Radio emission mechanisms: continuum surveys vs HI surveys
Questions in cosmology + Probes in the radio

Results:

1. Forecasting cosmological constraints using an HI survey – ISW tomography
   => potential to detect non-zero sound speed of dark energy

2. Forecasting cosmological constraints using future radio continuum surveys
   clustering: power spectrum ISW, lensing magnification
   => interesting constraints on modified gravity

3. Clustering and bias of radio continuum sources in FIRST survey
   Real data much harder than theory!
   Interesting constraint on bias of radio galaxies at z~0.7

4. Clustering and bias of HI sources in ALFALFA
   HI-selected galaxies anti-biased wrt DM (NB for SKA predictions)

5. Exploring probes of GR using HI data
   potential to reconstruct potential from TF estimates of peculiar velocities
Reflections

Considered:
clustering, ISW, some lensing, peculiar velocities

Not considered:

Redshift space distortions
Dark ages (before stars & quasars but potentially HI signatures)
Reionisation (HI signatures tracing early structures)
Pulsars as probe of gravity waves, GR
Lensing – shear near clusters, power spectrum – eMerlin proposal, heroic efforts on FIRST
Intensity mapping
Fine structure constant variations?
Radio detection of supernovae, gamma ray bursts
Polarisation?
What angles probe what z?

* although $dN/dz$ peaks above $z \sim 1$ for unmatched sample, $w$ probes lower $z$

* at small angle: sidelobe/multicomponent questions

* at large angle: physical scales large at high-z where no clustering power
### Assumed description for SKA1 and SKA2

<table>
<thead>
<tr>
<th>Collector type</th>
<th>SKA1_low</th>
<th>SKA1_mid</th>
<th>SKA2_low</th>
<th>SKA2_mid_dish</th>
<th>SKA2_AIP_AA</th>
<th>AIP_PAF</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>0.07 – 0.45</td>
<td>0.45 – 3.0</td>
<td>0.07 – 0.45</td>
<td>0.45 – 10</td>
<td>0.4 – 1.4</td>
<td>0.45 – 3.0</td>
<td>50MHz goal</td>
</tr>
<tr>
<td>Max bandwidth</td>
<td>0.38 [1]</td>
<td>1.5 [8]</td>
<td>0.38 [2]</td>
<td>Depends on feed</td>
<td>1.0 [8]</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Dish feeds: 1. GHz</td>
<td></td>
<td>0.45 – 0.9</td>
<td>To be decided</td>
<td></td>
<td></td>
<td>0.45 – 0.9</td>
<td></td>
</tr>
<tr>
<td>2. GHz</td>
<td></td>
<td>0.8 – 1.6</td>
<td></td>
<td></td>
<td></td>
<td>0.8 – 1.6</td>
<td></td>
</tr>
<tr>
<td>3. GHz</td>
<td></td>
<td>1.5 – 3.0</td>
<td></td>
<td></td>
<td></td>
<td>1.5 – 3.0</td>
<td></td>
</tr>
<tr>
<td>Effective FoV</td>
<td></td>
<td>1.0 [1]</td>
<td>200 [4]</td>
<td>1GHz: 1.0 [1]</td>
<td></td>
<td>0.5GHz: 144 deg²</td>
<td>15m dish FoV</td>
</tr>
<tr>
<td>1GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. of beams</td>
<td>160 [1]</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>36</td>
<td></td>
</tr>
<tr>
<td>Sensitivity / element</td>
<td>m²K⁻¹</td>
<td>7.2 [8]</td>
<td>1.2GHz: 4.0</td>
<td>&gt;90MHz: 14.3</td>
<td>4.0 [8]</td>
<td>&lt;1.2GHz: 36</td>
<td>1.2GHz: 3.5</td>
</tr>
<tr>
<td>Total sensitivity</td>
<td>m²K⁻¹</td>
<td>1,515 [1]</td>
<td>1.2GHz: 1,031</td>
<td>&gt;90MHz: 4,000</td>
<td>10,000 [2]</td>
<td>&lt;1.2GHz: 10,000</td>
<td>Sensitivity of AA on boresight</td>
</tr>
</tbody>
</table>
Other Simulations:

Intensity Mapping
- detection of HI averaged from many galaxies
- cross-correlation with optical galaxies
- (in eg DEEP2, Chang et al)

Other:
* beyond lambda CDM: WDM, exotic cosmologies?
* Radio continuum as a noise source
* OH, detailed galaxy sims
Exotic Cosmologies

Tests of GR on galaxy scales as in Jain et al

1. stellar disk displaced from gas/dust disk
2. warps
3. asymmetry
4. gas rotation enhanced with respect to stars

Tests on larger scales eg lensing potential vs velocity potential
**MeerKAT:**

- **South African precursor to Square Kilometer Array:**
  - 64 dishes (13.5m diam, offset gregorian)
  - Phase I: 0.7-1.7GHz & 8-14GHz, 8km baselines
  - Later: 8-14GHz and 20-60km baselines
  - ~5 years (44 kilohour) given to surveys listed here
  - Science by 2016, currently 7 dishes (KAT7)

**TRAPUM:**
- 3khr
- Fast transients
- PI Stappers & Kramer

**Pulsar Timing:**
- 8khr
- Test GR
- In blackhole-pulsar binary
- Gravi. Waves using pulsar array?
- PI Balles

**LADUMA:**
- 5khr
- Deep HI single pointing
- ~1-4sq.deg to z~1,
  - “vuvuzela” survey volume
- PI Baker, Blyth, Holwerda

**ThunderKAT:**
- 3khr
- Slow transients
- PI Fender & Woudt

**MeerGAL:**
- 3.3khr
- Galactic plane survey
- 8-14 GHz
- HII regions, masers, OB star mass loss, dust
- PI Thompson & Goedhart

**MIGHTEE:**
- 2khr
- Continuum survey
- 35sq.deg to 1μJy
- 0.1sq.deg to 0.1μJy
- Faint radio AGN, starforming galaxies & relics in clusters
- PI Jarvis & vanderHeyden

**MALS:**
- 4khr
- Absorption Line Survey
- Pointed at 2000 brightest radio continuum sources
- HI & OH absorption stats
- Fundamental constants?
- PI Gupta & Srianand

**MHONGOOSE:**
- 6khr
- HI in 30 nearby Galaxies
- Dark matter studies, cold accretion, cosmic web
- PI de Blok

**FORNAX:**
- 2.5khr
- HI in Fornax cluster
- PI Serra

**MESMER:**
- 6.5khr
- HI in Fornax cluster
- Z>7 CO survey
- 1. Point at clusters
- 2. Point at quasars
- 3. Blank fiels
- PI: Heywood